FINAL TECHNICAL REPORT

TO THE

AIRFORCE OFFICE OF SCIENTIFIC RESEARCH

"LIMIT CYCLE OSCILLATIONS (LCO) AND

NONLINEAR AEROELASTIC WING RESPONSE:

REDUCED ORDER AERODYNAMIC MODELS"

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13. ABSTRACT *(Maximum 200 words)*

A nonlinear, aeroelastic analysis of a low aspect, delta wing modeled as a plate of constant thickness demonstrates that limit cycle oscillations (LCO) of the order of the plate thickness are possible. The structural nonlinearity arises from double bending in both the chordwise and spanwise directions. The present results using a vortex lattice aerodynamic model for a low Mach number flow complement earlier studies for rectangular wing platforms that showed similar qualitative results. The theoretical results for the flutter boundary (beyond which LCO occurs) have been validated by comparison to the experimental data reported by other investigators for the low aspect ratio delta wings. Also the limit cycle oscillations found experimentally by previous investigators (but not previously quantified prior to the present work) are consistent with the theoretical results reported here. Reduced order aerodynamic and structural models are used to substantially decrease computational cost with no loss in accuracy. Without the use of reduced order models, calculations of the LCO would be impractical. A wind tunnel model is tested to provide a quantitative experimental correlation with the theoretical results for the LCO response itself.

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OBJECTIVE

To develop an eigenmode or proper orthogonal decomposition (POD) modal representation of unsteady aerodynamic forces on oscillating airfoils and wings and thereby reduce the size and cost of mathematical models of such forces by several orders of magnitude. As an interim and alternative investigation, consider semi-empirical models based upon theory and experiment to assess the effect of stall and separated flow nonlinearities on limit cycle oscillations of aeroelastic systems.

STATUS OF EFFORT

Eigenmode and POD representations have been successfully constructed for isolated airfoils and for airfoils in cascade using potential flow models, the Euler fluid equations of motion and, for viscous flows, a potential flow plus boundary layer model. OUR MOST RECENT RESULTS ARE FOR TRANSONIC FLOWS WITH SHOCK WAVES INCLUDING VISCOUS BOUNDARY LAYER EFFECTS. THESE RESULTS ARE FOR SMALL, DYNAMICALLY LINEAR MOTIONS ABOUT A NONLINEAR STEADY FLOW.

Current work is underway to extend this work to NONLINEAR, DYNAMIC MODELS of transonic, viscous flows using either eigenmodes or modes determined from Proper Orthogonal Decomposition (POD). The latter are also sometimes called KL modes using the initials of the two inventors of these modes [1-9].

For wings and three-dimensional flow fields, incompressible potential equations have been used to construct reduced order models. Current work is to extend this achievement to compressible potential and Euler equations of motion.

All reduced order modeling studies completed to date suggest that 50 or fewer aerodynamic modes are required for aeroelastic analyses and often the number of modes needed is fewer than 10 for many parameter combinations. By contrast the original computational fluid dynamic models studied to date have as many as 30,000 degrees of freedom, and in their original form are not practical for aeroelastic design methods.

In addition, an experimental study has been made of bodies typical of wing and tip stores to determine stall and separated flow effects on limit cycle oscillations (LCO) [10]. This work suggests the effects are only important at very large angles of attack, i.e. typically greater than 20° at low speeds. Of course, such effects may occur at smaller angles under transonic flow conditions.

Also, the nonlinear aeroelastic behavior of a delta wing in low speed flow with plate-like structural nonlinearities has been investigated recently [11]. It has been shown that a benign limit cycle oscillation (LCO) occurs for flow velocities in excess of the linear, flutter velocity. THIS SUGGESTS AIRCRAFT DESIGNED TO HAVE THIS TYPE OF STRUCTURAL NONLINEARITY MAY BE FLOWN SAFELY UP TO THE LINEAR FLUTTER VELOCITY AND SOMEWHAT BEYOND.

ACCOMPLISHMENTS

The successful construction of eigenmode aerodynamic models has led to reductions in computational times for aeroelastic analyses of up to four orders of magnitude, I.E. A REDUCTION IN COMPUTATIONAL COST BY A FACTOR OF UP TO 10^4. THIS PERMITS FOR THE FIRST TIME THE USE OF STATE-OF-THE-ART COMPUTATIONAL FLUID DYNAMICS (CFD) MODELS IN AEROELASTIC ANALYSES FOR DESIGN PURPOSES. Also, greater insight into critical physical phenomena has been obtained by the observation and study of the interaction between the fluid eigenmodes and the well known structural modes.

An exploratory aeroelastic study for a simple delta wing with plate-like structural nonlinearities suggests such wings may be flown safely up to the linear flutter velocity and beyond. THIS GIVES PROMISE OF PROVIDING A WAY FOR THE DESIGNERS TO CONSIDER REDUCED FLUTTER MARGINS AND THEREBY ENHANCE PERFORMANCE AND SAFETY.

Attached is an abstract of a paper presented at the AIAA Aerospace Sciences (Reno) Meeting describing some of our most recent results for transonic flows [12]. Also attached are two abstracts for the AIAA SDM Meeting in St. Louis. One is an invited overview paper on our reduced order modeling work [13] and the other describes our recent work on delta wings with structural nonlinearities where the use of reduced order aerodynamic models is an essential enabling technology [11].

PERSONNEL SUPPORTED BY PARENT AFOSR GRANT

- Earl Dowell, Professor

- Deman Tang, Research Associate

- Jeffrey Thomas, Research Assistant Professor

- Bogdan Epureanu, Graduate Student/Research Assistant

Other personnel involved in the total effort have been supported by NASA and NSF. Of these, special mention should be made of my faculty colleague, Professor Kenneth Hall.

PERSONNEL SUPPORTED BY AASERT AWARD

- Jonathon Nicholas, Graduate Student.

PUBLICATIONS

1. Hall, K.C., "Eigenanalysis of Unsteady Flows About Airfoils, Cascades and Wings", AIAA Journal, Vol 32, No. 12, 1994, pp. 2426-2432.

2. Hall, K.C. and Florea, R., "Reduced Order Modeling of Unsteady Flows About Airfoils", Presented at the ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, November 7-11, 1994.

3. Hall, K.C., R. Florea, and Lanzkron, P.J., "A Reduced Order Model of Unsteady Flows in Turbomachinery", Presented at the International Gas Turbine and Aeroengine Congress and Exposition, the Hague, Netherlands, June 13-16, 1994.

4. Mahajan, A.J., Bakhle, M.A., and Dowell, E.H., "A New Method for Aeroelastic Stability Analysis .of Cascades Using Nonlinear, Time Marching CFD Solvers", AIAA 94-4396, Presented at the 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City Beach, FL, September 7-9, 1994.

5. Romanowski, M.C., and Dowell, E.H., "Using Eigenmodes to Form an Efficient Euler Based Unsteady Aerodynamics Analysis", Presented at the ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, November 7-11, 1994.

6. Romanowski, M.C., and Dowell, E.H., "Reduced Order Euler Equations for Unsteady Aerodynamic Flows: Numerical Techniques", Presented at the AIAA Aerospace Sciences Meeting, January, 1996.

7. Dowell, E.H., "Eigenmode Analysis in Unsteady Aerodynamics: Reduced Order Models", Presented at the 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, New Orleans, LA, April 10-12, 1995. AIAA Journal, Vol. 34, No. 8, 1996, pp. 1578-1583.

8. Romanowski, M., "Reduced Order Unsteady Aerodynamic and Aeroelastic Models Using Karhunen-Loeve Eigenmodes", AIAA Paper 96-2572. AIAA Symposium on Multidisciplinary Analysis and Optimization. Bellevue, WA, Sept., 1996.

9. Dowell, E.H., Hall K.C. and Romanowski, M.C., "Eigenmode Analysis in Unsteady Aerodynamics: Reduced Order Models", Applied Mechanics Reviews, Vol. 50, No. 6, 1997, pp. 371-386.

10. Tang, D.M. and Dowell, E.H., ""Unsteady Aerodynamics Forces and Aeroelastic Response for An External Store for An Aircraft", submitted to Journal of Aircraft for publication.

11. Tang, D.M., Henry, J.K. and Dowell, E.H., "Limit Cycle Oscillations of Delta Wing Models in Subsonic Flow", to be presented at the AIAA SDM Conference, St. Louis, Spring, 1999.

12. Hall, Kenneth C., Thomas, Jeffrey P. and Dowell, E.H., "Reduced Order Modelling Of Unsteady Small-Disturbance Flows Using A Frequency-Domain Proper Orthogonal Decomposition Technique", to be presented at the AIAA Aerospace Sciences Meeting, Reno, January, 1999.

13. Dowell, E.H., Hall, K.C., Thomas, J.P. and Florea, R., "Modal Analysis In Unsteady Aerodynamics: Reduced Order Models", to be presented at the AIAA/SDM Conference, St. Louis, Spring, 1999.

INTERACTIONS/TRANSITIONS

We continue to interact closely with Dr. Walter Silva of the NASA Langley Research Center Aeroelasticity Branch and Dr. Larry Huttsell of the Air Force Research Laboratory Aeroelasticity Group on reduced order modeling. Also regular presentations are made to the semi-annual meetings of the Aerospace Flutter and Dynamics Council, chaired by Rudy Yurkovich of the Boeing Company. Dr. John Kim of the Boeing Company is pursuing reduced order models for industrial use based upon the methodologies developed under this AFOSR grant.

This past year, Rudy Yurkovich and Dr. Philip Beran of AFRL presented seminars and held technical discussions at Duke University.

DISCOVERIES, INVENTIONS, PATENTS

None

HONORS/AWARDS

Lifetime Recognition:

Earl H. Dowell

- Member/National Academy of Engineering

- Fellow

  - American Institute of Aeronautics and Astronautics
  - American Society of Mechanical Engineers
  - American Academy of Mechanics

- Recipient

  - AIAA Structures, Structural Dynamics and Materials Award (the most significant research award in this field)
  - American Academy of Mechanics Distinguished Service Award.

ATTACHMENT 1

"Reduced Order Modelling Of Unsteady Small-Disturbance Flows Using
A Frequency-Domain Proper Orthogonal Decomposition Technique"

by
Kenneth C. Hall, Jeffrey P. Thomas and Earl H. Dowell
Duke University, Durham

A new method for constructing reduced order models (R.O.M.) of unsteady small-disturbance flows is presented. The reduced order model is constructed using the basis vectors determined from the proper orthogonal decomposition (P.O.D.) of an ensemble of small-disturbance frequency-domain solutions. The individual frequency-domain solutions are computed using a very efficient time-linearized flow solver. In this extended abstract, we show for a model flow problem that reduced order models can be constructed using just a handful of P.O.D. basis vectors, producing low-order but highly accurate models of the unsteady flow over a wide range of frequencies. In the final paper, we will also apply the technique to more complex flow fields, e.g., unsteady flow in a turbomachinery cascade.

In recent years, a number of researchers have used the proper orthogonal decomposition (P.O.D.) technique, also known as Karhunen-Loeve [1] expansions, to determine and model coherent structures in turbulent flow fields. Lumley [2] was the first to propose using proper orthogonal decomposition to determine coherent structures in turbulent flow fields. Other examples include the pioneering works by Lumley et al. [2,3,4], Sirovich et al. [5,6,7], Moin and Moser [8], Rempfer and Fasel [9,10], and Deane et al. [11]. A recently published book by Holmes, Lumley and Berkooz [12] provides an overview of the P.O.D. method along with extensive details of how the method has been used by researchers to study a wide variety of fluids problems.

Recently, several researchers have used the P.O.D. technique to construct reduced order models (R.O.M.) of unsteady aerodynamic flows. Romanowski [13], for example, has used the P.O.D. technique to create a reduced order aeroelastic model of a two-dimensional isolated airfoil, including compressible aerodynamics. Romanowski has shown that very accurate unsteady flow models can be constructed that reduce the number of degrees of freedom from the thousands associated with the original CFD flow solver to a few tens of degrees of freedom. Tang et al [14] have investigated using the P.O.D. technique to create a reduced order model that may then be used to design an active control system.

Most of the previous work using proper orthogonal decomposition has used data sampled from the time domain, or from ensembles of steady data as in the case of graphical feature recognition. In this paper, we use an alternative approach. Here, we use a time-linearized CFD analysis to compute unsteady small-disturbance flow solutions in the frequency domain over a range of frequencies. Basis vectors are then extracted from this frequency-domain data set using P.O.D. methods. Finally, the basis vectors are used to construct low degree of freedom reduced order models of the unsteady flow.

ATTACHMENT 2

"Modal Analysis In Unsteady Aerodynamics: Reduced Order Models"

by
Earl H. Dowell, Kenneth C. Hall, Jeffrey P. Thomas and
Razvan Florea
Duke University, Durham

In this article, we review the status of reduced order modeling of unsteady aerodynamic systems. Reduced order modeling is a conceptually novel and computationally efficient technique for computing unsteady flow about isolated airfoils, wings, and turbomachinery cascades. Starting with either a time domain or frequency domain computational fluid dynamics (CFD) analysis of unsteady aerodynamic or aeroacoustic flows, a large, sparse eigenvalue problem is solved using the Lanczos algorithm. Then, using just a few of the resulting eigenmodes, a Reduced Order Model of the unsteady flow is constructed. With this model, one can rapidly and accurately predict the unsteady aerodynamic response of the system over a wide range of reduced frequencies. Moreover, the eigenmode information provides important insights into the physics of unsteady flows. Finally the method is particularly well suited for use in the active control of aeroelastic and aeroacoustic phenomena as well as in standard aeroelastic analysis for flutter or gust response. As an alternative to the use of eigenmodes, Proper Orthogonal Decomposition (POD) is also explored and discussed. In general POD is an attractive alternative to the use of eigenmodes in terms of computational cost and convenience. Numerical results presented include:

1)   comparison of the reduced order model to classical unsteady incompressible aerodynamic theory,

2)   reduced order calculations of compressible unsteady aerodynamics based on the full potential equation,

3)   reduced order calculations of unsteady flow about an isolated airfoil based on the Euler equations, and

4)   reduced order calculations of unsteady viscous flows associated with cascade stall flutter,

5)   flutter analysis using the Reduced Order Model.

Recent results for transonic flows with shock waves including viscous and nonlinear effects are emphasized.

"Limit Cycle Oscillations Of Delta Wing Models
In Low Subsonic Flow"

by
Deman Tang, James K. Henry and Earl H. Dowell
Duke University, Durham

Presented at the AIAA SDM Conference
in St. Louis, Spring, 1999

A nonlinear, aeroelastic analysis of a low aspect, delta wing modeled as a plate of constant thickness demonstrates that limit cycle oscillations (LCO) of the order of the plate thickness are possible. The structural nonlinearity arises from double bending in both the chordwise and spanwise directions. The present results using a vortex lattice aerodynamic model for a low Mach number flow complement earlier studies for rectangular wing platforms that showed similar qualitative results. The theoretical results for the flutter boundary (beyond which LCO occurs) have been validated by comparison to the experimental data reported by other investigators for low aspect ratio delta wings. Also the limit cycle oscillations found experimentally by previous investigators (but not previously quantified prior to the present work) are consistent with the theoretical results reported here. Reduced order aerodynamic and structural models are used to substantially decrease computational cost with no loss in accuracy. Without the use of reduced order models, calculations of the LCO would be impractical. A wind tunnel model is tested to provide a quantitative experimental correlation with the theoretical results for the LCO response itself.

Linear and nonlinear aeroelastic responses of panels or plates with fixed supports on all four sides have been studied for many years from subsonic to supersonic flow, see Ref. [1] and [2]. More recently plates with free edges have been studied and these results (Ref.[3]-[4]) have provided good physical understanding of the flutter and limit cycle oscillation characteristics for such plates in a high Mach number supersonic flow. In particular, it has been demonstrated that even with only a single edge of a plate restrained, bending tension or geometrical nonlinearities can produce limit cycle oscillation amplitudes of the order of the plate thickness. For low subsonic flow speeds Ref. [5] used a three-dimensional time doman vortex lattice aerodynamic model and reduced order aerodynamic technique [6], [7] to investigate the flutter and limit cycle oscillation characteristics of a cantilevered low aspect ratio, rectangular wing-panel structure. Again limit cycle oscillations were found.

Following the work of Ref. [5], in the present paper we also use the vortex lattice aerodynamic model to investigate the flutter and limit cycle oscillation characteristics of a low aspect ratio delta wing structure at low subsonic flow speeds. The theoretical results are consistent with the experimental results of Doggett and Solstmann

[8] who previously studied the flutter of low aspect ratio delta wings.

In order to validate the theoretically predicted limit cycle oscillation characteristics of the
delta wing, an experimental investigation has been carried out in the Duke wind tunnel using an
Ometron VPI 4000 Scanning Laser Vibrometer system [11] to measure deflections (velocities) of the delta wing. The VPI sensor is a non-contacting transducer that uses optical interferometry and electronic frequency measurements to determine the frequency shift of a beam of light reflected from a moving surface.

Theoretical and experimental results show good agreement. The present results suggest a new approach to retaining structural integrity of flexible wings in a post-flutter environment.

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